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SOLID STATE REMOTE POWER CONTROLLERS FOR 120 VDC POWER SYSTEMS

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INTRODUCTION

Conventional power distribution systems require a series of mechanical circuit breakers, relays, and fuses to perform the needed functions of load switching and of total system protection of equipment and wires. As distribution and transmission systems grow in size, sophistication, and complexity, however, so do the requirements for the power control and protection equipment. Studies by NASA and the Navy reveal significant system benefits in efficiency, weight, cost, reliability, and design flexibility, if aircraft and spacecraft power distribution and transmission is done at dc voltages above 100 Vdc rather than at conventional 28 Vdc and/or 115 Vac levels.[1,2,3,4] One of the stated major roadblocks delaying the development and use of high voltage dc on air- or spaceflight vehicles has been the lack of suitable switchgear.

A NASA Lewis Research Center development contract with Westinghouse's Aerospace Electrical Division has developed solid state remote power controllers (RPCs) for use in any dc power system with voltage up to 120 Vdc and distributed power up to 3.6 kW per bus.[5] These RPCs have been demonstrated to be reliable, 99% efficient, comparatively simple and potentially low in cost.

RPCs are devices that combine in one unit the capability to perform all the needed functions of load switching and provide total system protection of equipment and wires. In addition solid state RPCs possess several added advantages that contribute directly to power system benefits. These advantages include: "contactless" switching (no contact wear or arcing); controlled rates of current rise and fall; current limiting; fast, well-defined, repeatable response to overloads and faults especially over temperature extremes; e.g., -55° to 100° C. Additional features of the solid state RPCs include internal dI/dt limiting without use of inductors, giving the RPC an essentially infinite surge capability, and optical isolation of the remote control and remote status indication from the power bus. Their EMI generation and susceptibility levels also meet or exceed all Mil-Std-461A requirements. Figure (1) illustrates a typical RPC application.

The NASA development program in dc switchgear has established the advantages of solid state RPCs while seeking to reduce their drawbacks of higher power losses and complicated, costly designs as compared to conventional switchgear. A substantial achievement of this work is solid state RPCs that have nearly a 99% efficiency with dramatically simplified circuits. Also, their off-state power losses are virtually zero. The simplified designs use a Darlington switch and typically require less than 90 piece parts. These designs will bring solid state RPC costs down substantially and provide direction for standardization concepts of the control and drive circuits. With this standardization a possibility then essentially only the power transistors will have to be changed to accommodate higher voltage applications. This simplification and uniformity of the basic control and drive circuits also paves the way for hybridization of the RPCs to reduce their weight and volume for aerospace applications.

These steps are significant when we consider that large power systems on vehicles such as the Space Shuttle, a future Space Station, or military aircraft will require well over 250 RPCs or other protective devices. This paper then will review the unique developments of the solid state RPC as it benefits 120 Vdc power distribution systems.

DESIGN GUIDELINES

The basic design guidelines with specific requirements and system advantages for the 120 Vdc solid state RPCs are summarized in Table I.

A. Power Stage Considerations

In addition to the design guidelines several design goals were established as follows for the RPCs:

- Circuit simplicity was a high priority; specifications could be (and were) modified if justified;
- Special or selected components would be eliminated if possible;
- Inductors and magnetic components would be eliminated where possible;
- The RPCs were to function over as wide a voltage range as possible without impairing efficiency at rated voltage;
- The RPCs were to be compatible with all source types, especially ones with low impedance and capable of supplying high current surges (>1000 amps).

Of significance for 120 Vdc applications is the development of three types of RPCs with two types having a 5-ampere current rating and one type a 30-ampere rating. All three types have their trip characteristics coordinated to permit the series/parallel operation of the RPCs in a distribution system. Also of significance is the inherent capability of the RPC designs to control the ultimate current resulting from an applied zero impedance fault with no passive dI/dt limiting, i.e., no inductors. Response time to any applied fault is typically less than 3 μsec with peak currents during this time limited to three times the maximum current capacity of the RPC. This response time has been verified with a 4500-ampere source and a cumulative loop inductance well below that which is anticipated for any practical power system.

Two fundamental types of protection are available in the RPC. The first type has current limiting at 3X (three times rated current) for 0.1 second before tripout for fault currents greater than 3X.[6] This current limited trip is coordinated with an I^2T trip response for overload currents less than 3X but larger than 1.2X. The second type RPC is non-current limiting with selectable instant trip current levels up to 5X and has a compatible I^2T trip curve for overcurrents greater than 1.2X but less than the instant trip level.

Table II is a performance summary of the 120 Vdc RPCs. The ratings and characteristics are shown for all three types and both design generations. Tables I and II along with Figures (2) to (4) comprise a rather complete listing of the ratings, characteristics, and capabilities of these RPCs. With regard to the trip curves it should be noted that all the devices respond according to these curves within ±5% over the entire temperature range of -55^{o} to 100^{o} C. In Table II the component number and cost figure in parenthesis for the simplified Type III RPC is the final parts count for the hybrid design breadboard. Five additions pass transistors and their associated emitter resistors were added to provide a safety margin to handle the steady-state power dissipation in the hybrid configuration.

B. Control/Status Considerations

Of interest in a distribution system application is the feasibility for computer control and interrogation of the RPCs in the electrical system. This feasibility is enhanced by the low control power and the solid-state logic required at the RPC interface. Thus, if the RPC has status information available for interrogation, then a computer can be

used to detect system failures and take corrective action. For this reason it is important that the RPCs control/status format be compatible with a computer input/output (I/O) terminal and convey all necessary information for two-way communication.

In a trade-off study for the RPCs we reviewed performance, relative merits, and cost comparisons of various existing and new concepts related to the control/status logic configuration. In this particular case all the basic concepts fall into two fundamental systems, namely, analog and digital. A comparison summary of the two systems is given in Table III.

An analog system requires a constant current control supply and uses only two wires for control and status indication.[7] The impedance of the control input to the RPC is sensed by an analog sensor at the I/O terminal to determine status condition. It requires a relatively slow analog to digital conversion step plus some rather complex circuitry in the RPC itself to sense status. However, the amount of available information in terms of distinguishable states is limited only by the noise and accuracy of the system.

A digital system requires a constant voltage control supply and uses a minimum of three wires for control and status indication. Logic states "1" and/or "0" are sensed directly at the I/O terminals of the RPC. The status sampling multiplexer (at the I/O unit) may be all digital with the three wires and number of discernable states adequate to resolve ON, OFF, and TRIPPED states. The status indication can be a simple sink signal derived in a circuit where the I/O unit supplies the power and the sinking logic can easily be fashioned from a transistor and an inexpensive opto-coupler.

Both systems have advantages and drawbacks, but are essentially compatible in principle with computer control. Also, both systems provide optical coupling for dielectric, transient voltage, and EMI isolation of the power and control circuits. However, it was concluded that the digital (current sinking) approach was the most cost effective for control/status configuration. The digital system results in the simplest, most reliable RPC and the preferred system approach for most potential NASA applications. The additional (signal level) wire needed for the digital system is a less severe penalty than the problems and complexities associated with the analog conversion system required on each RPC.

POWER SWITCH DESIGN CONCEPTS

A. General Requirements

All of the RPC subcircuit functions and their inter-relationships are illustrated by the functional block diagram, Figure (5). The dashed lines indicate current limiting and automatic reset options. The biggest design challenge in the RPC is the power switch, which must withstand applied faults at the load, i.e., between the power output terminal and ground. For the worst case (shorted load) in the Type I, the power switch must handle 15 amps times 132 volts or 1980 watts for 0.1 second. Additionally, the switch must change quickly from the fully saturated state to a voltage blocking, current limiting state, upon application of a short circuit, without passing damaging (to the RPC) transitional current spikes.

Types II and III RPCs have no current limiting requirements, but they must pass, respectively, up to 5 and 3 times rated current without damage or sacrifice of electrical efficiency at rated current conditions. Also, the RPC power switch must be self protected against the rapid buildup of current resulting from a step applied fault, that is, it must have some form of dI/dt limiting. The power switch must control the current to safe levels while the trip circuit processes an "instant trip" signal to turn the power switch off. During this processing time the load current through the power switch will rise to several times the trip level. Either the power switch and its power circuit or the power switch control circuit must be able to handle or contain this

current overshoot immediately.

Because of the above general requirements the transistor was selected as the basic power switching element in preference to an SCR or a gate turn-off thyristor. The transistor also offers the lowest forward voltage drop and is the easiest to control under all conditions.

B. Transistor Power Switch

Several practical limitations place constraints on the power switch design. In any RPC design for reasons of safety and fail safe operation the hot or ungrounded side of the load must be switched. On this basis a PNP transistor, which requires simpler drive than an NPN transistor, is best suited to this arrangement as shown in Figure (6A). However, a device search revealed that no PNP devices that would satisfy the 120 Vdc RPC requirments are available on today's market. Therefore, an NPN transistor must be used as the basic switch element.

In order to saturate an NPN transistor its base voltage must be above its collector voltage as shown in Figure (6B). Since the RPC is required to be self powered from the load bus, some sort of transformer-oscillator or other type driver circuit is needed to provide the higher base voltage. The driver circuit is further needed from an efficiency standpoint. For example, even if the circuit of Figure (6A) were used with no transformer, the ultimate electrical efficiency of the power stage would be $1 - 1/\beta_{sat}$ or 90% for a transistor with a saturation gain of 10 and a saturation voltage drop of zero volts. This efficiency is unacceptable and can be improved either by using special high gain PNP transistors (which is unlikely) or by the turns ratio of a transformer oscillator drive circuit or by using a Darlington configuration power switch.

Figure (7) illustrates the original power switch design that combines the best features of both a transformer oscillator design and a transformerless design. The efficiency of the power stage is optimized by the transformer oscillator driver and the control response is fast through Q_2 and Q_3. The level of saturation of the power transistor, Q_1, is controlled by transistors, Q_2 and Q_3, and is relatively independent of the transformer-oscillator time constant. Therefore, the response of the power switch to faults is not limited by the oscillator response and can be made as fast as a transformerless design. During current limiting, when Q_1 is not in saturation, Q_2 and Q_3 are in an active mode and, therefore, very little noise from the oscillator output is coupled into Q_1.

An additional performance feature of this circuit is its ability to pass higher than rated current without sacrifice of increased dissipation (resulting from overdrive) at rated load current. The practical upper efficiency limit of this circuit can be shown to be 99.2% for a 5-ampere, 120 Vdc design.

During the circuit design phase leading to Figure (7), it became apparent that substantial improvements could be made in performance by eliminating the transformer-oscillator driver circuit. Figure (8) shows the second generation, simplified power switch using a Darlington configuration, which reduces complexity, cost, and radio noise generation with an increase in reliability. These improvements are realized at the expense of an increase of forward voltage drop from 0.5 to 1.2 volts. However, the increased voltage drop and increased conduction power loss is offset by the lower drive losses required in the Darlington circuit. The demonstrated results reveal that both designs have comparable actual efficiencies between 98.5 and 98.7 percent.

An additional performance bonus of the Darlington is its partial load efficiency, which is superior to the transformer design. This occurs because as load current decreases, base drive to Q_1 is automatically reduced. Figure (9) illustrates this comparison for the Type I power stage. Since RPC ratings are discrete, the average loading in any given

system with many RPCs will never be 100%. Therefore, the partial load dissipation is an important consideration. A second performance bonus is a substantial increase in the operating voltage range from an 80 V minimum down to 25 V (see Table II).

The basic trade-offs between the transformer and Darlington designs hold for all three types of RPCs. The transformer design with its low forward drop (less than 0.5 V) does give a better system voltage regulation. However, the Darlington design simplifies the circuit, eliminates a source of EMI, reduces parts count and cost at no sacrifice in overall efficiency. The two performance bonuses, superior partial load efficiency and extended operating voltage range, coupled with the elimination of magnetics makes the Darlington design an attractive choice for building hybrid units for flight system applications.

C. Current Limiting Power Stage

Both Type I designs (transformer-oscillator and Darlington) used basically the same current limiting circuit. The current sensing and the feedback and control loops provide excellent current control and fast transient response under all fault conditions. Current limiting with the main power transistor alone places some rather severe power dissipation requirements on the transistor itself. The need to current limit at 15 amps and 132 volts simultaneously was not obtainable in any single NPN transistor. An alloy type transistor was selected because it offered a substantially better, although inadequate, safe operating area (SOA) capability than any other type.

The inqdequate SOA for the 120 Vdc current limiting application was remedied by using an SOA boost circuit. The circuit concept is shown in Figure (10). For purposes of discussion Q_1 and Q_2 are shown as PNP transistors. During normal non-current limiting conditions Q_1 is fully saturated and carries essentially all of the load current. During current limiting, Q_2 is saturated and as the voltage across Q_1 increases, current (and hence power) is diverged from Q_1 to the relatively low cost resistors, R_1 and R_2. Since the current limit control loop is closed around the load current, the circuit will limit load current to the desired level even though currents I_1 and I_2 may be changing. That is, at any instant in time, $I_1 + I_2 = I_{load} =$ constant, during current limiting. Obviously, the lower the value of R_1 and R_2 the more effective the boost becomes. In order to optimize the design Q_2 is allowed to drop out of saturation by Zener diode, Z_1. The voltage across Q_1 at which Q_2 is forced out of saturation is defined as V_φ and is a design parameter. This operation is illustrated by characteristic curves for this booster circuit and are shown in Figure (11). It should be noted that the maximum level of I_2 must be less than the current limiting level if current limiting is to remain constant up to 200 volts.

The final design of the original Type I power stage including the booster uses three Westinghouse Type 164-20 alloy transistors, one for Q_1 and two paralleled for Q_2. It meets the performance requirements established by NASA. Maximum current is limited to 15 amperes for 0.1 second, for any overload including short circuit and including voltage supply transients to 200 Vdc.

Since the original Type I power stage requires three relatively expensive alloy transitors and two power resistors to safely withstand the dissipation during short circuit current limiting, one cost reduction technique in the simplified RPC would be to eliminate the alloy transistors entirely. Such an arrangement is possible by putting all of the dissipation during current limiting into resistors (i.e., passive current limiting) and using lower cost transistors to switch in the proper amount of resistance. This type of design, however, gives poor current limiting quality, which can be improved only by increasing the number of resistors and switches, which in turn requires more complex sensing and control circuits.

A compromise solution to the problem was to reduce the number of high cost alloy transistors and relax certain design requirements to accommodate this reduction. This arrangement resulted in a simple circuit design yet provided good current limiting characteristics. Figure (12A) illustrates the circuit concept. It uses a simple (passive) helper circuit rather than the original active helper circuit. Although the complexity is changed very little, the cost is improved 40 to 50 dollars for each alloy transistor (type 164) that is eliminated or replaced with a switching transistor.

The effect on the current limiting quality is also illustrated by Figure (12). The original design, Figure (12A), utilized the active helper and was capable of 3X current limiting at rated supply voltage (120 Vdc) as well as during a 200-volt, 50-microsecond transient with a shorted load. The simplified current limiting circuit performs essentially the same except that the helper remains in saturation and hence cannot limit load current to 3X for switch voltage levels above V_{3X}. Thus, a lower power transistor can be used for Q_2.

Parametric studies were made to select the optimum current limiting performance of the simplified circuit. These studies resulted in a variety of current limiting possibilities as a function of cost. The characteristic finally selected is shown by Figure (13). The corresponding circuit uses one alloy transistor and can operate up to 100° C with a 0.1 second short circuit current limit time.

D. Non-Current Limiting Power Stage

The non-current limiting power stage is essentially the same as the basic power switch shown in Figure (7) except the oscillator primary current and the control current (I_{R1}) can be combined into one and, thereby, improve efficiency. This circuit change improved the efficiency of the Types II and III power stages by 0.1% over the Type I power stage.

The simplified Types II and III power stage is essentially the same as the simplified Type I power switch except for the current limit control and the deletion of the passive helper circuit as shown in Figure (14). Feedback capacitor, C_1, and the current sensing shunt, R_1, serve to limit the peak current and provide dI/dt limiting.

Resistor R_1 is a low voltage current sensing shunt, which provides current magnitude information to the trip circuit for overload tripout. Capacitor, C_1, also uses this voltage to help control the peak amplitude of the load current for the worst case step applied fault. Capacitor, C_1, produces a short-term current limiting function (through Q_1, Q_2, and Q_3), which is capable of limiting maximum current during the few microseconds that the trip circuit is processing an "instant trip" signal. The capacitor has the effect of making the power stage appear somewhat inductive for step applied faults. As a result, the power stage inherently provides dI/dt limiting and no line inductors are needed to protect the Types II and III non-current limiting RPCs.

Experimental results have verified compatibility with a test system having a 4000+ ampere source capability and low inductance, 0.1 farad output capacitor and 10 to 25 feet of No. 2 copper cable. This setup is considered to represent a more severe fault condition than would exist in a real system.

E. Control and Trip Circuits

The purpose of the control circuit is to interface with low power external signals to provide on-off control and to provide the necessary logic for trip free operation, automatic reset, and status indication. Opto-couplers interface with the power circuit and provide 1000 Vac, 60 Hz, dielectric isolation between the low power control/status side and the high power side of the RPCs. The trip circuit monitors the magnitude of the load current and provides a trip signal to the control circuit. The trip time delay for the RPC is generated by a linear circuit,

which approximates the NASA requirements very closely. Comparison of the linear equations with the specified equations (as shown in figs. 2, 3, and 4) illustrates the closeness of approximation. The design problems encountered on the control and trip circuits were conventional in nature and did not require extensive development; therefore, detailed circuit designs are not covered in this paper.

PERFORMANCE SUMMARY

A total of 12 RPC units have been constructed and evaluated to date. The hardware consists of six breadboards and six engineering models. The breadboards include one of each type and one of each generation. The engineering models include two of each of the three types in the original, transformer-oscillator, power switch design. The engineering models were placed in non-hermetically sealed packages. The evaluation consisted of recording all pertinent performance parameters at -55^{o}, $+25^{o}$, and $+100^{o}$ C. Included in the evaluation were fault tests to verify the short circuit capability of the RPCs. Table II is a summary of the $+25^{o}$ C test data taken on the 12 units.

The units were also evaluated in a series/parallel operation in a distribution system type connection, where one 30 amp unit feeds power to six 5 amp units, each feeding separate loads. Hence, it is important that the RPCs start up in the proper state and are self protecting in the event of an existing fault on an RPC or anywhere else in the system. The test results with all possible combinations of startup and faults gave satisfactory performance in coordination of trip characteristics and self protection.

HYBRID CIRCUIT AND PACKAGE DESIGN

Since the ultimate goal of this 120 Vdc RPC program is to demonstrate technology readiness, the final phase is directed to the design, fabrication, and testing of multi-chip hybrid prototypes in hermetically sealed packages. The simplified circuits of the three types with their low parts count, their greater versatility, their high efficiency, and their relative lack of bulky magnetic components are being hybridized. The final package design guidelines are as follows:

1. Minimize package size and weight,
2. Provide reliable thermal interface in a space environment,
3. Build and evaluate 10 RPCs,
4. Keep the design simple for minimum manufacturing costs,
5. Develop designs that are amenable to volume production, and
6. Build RPCs that can be "Qualified" when the need arises.

Figure 15 shows a three-dimensional cutaway of the hybrid Type I RPC. The Types II and III are similar in basic concept with the exception that they use only one substrate level and a larger base area. To minimize costs to this program the Type II RPC was built on a Type III header assembly, since they are essentially identical circuit-wise, except the Type II requires fewer power transistors. It should be noted that this decision gives a non-optimized Type II design, which turns out to be almost as large and heavy as the Type III rather than smaller and lighter than a Type I as might be expected.

The other designs were optimized for size and weight, for thermal considerations, for volume production, and for possible flight qualification. One point of reference for these design decisions was the Westinghouse experience on the 28 Vdc Space Shuttle RPCs already designed and in production.

A detailed thermal analysis for all three types has been performed to establish maximum temperatures for critical parts during both steady operation and worst case overload conditions. The two major areas of concern thermally were the transient analysis of the Type I during current limiting and the Type III under steady state operation. The primary heat flow path is from the beryllia substrate through the copper can wall and out the

base plate to the mounting surface. The header-to-can seal and the can design provide ease of assembly and positive metal contact to the heat sink for reliable thermal contact.

In preparation for possible need or desire to flight qualify the hybrid RPCs, a Reliability Prediction Analysis and a Failure Mode and Effects Analysis (FMEA) were performed on each of the three RPC types. The source of failure rates and the prediction procedure is MIL-HDBK-217B dated 20 September 1974. The predicted reliability depends predominantly on the RPC type and its base plate operating temperature. Assuming Mil-Std 883, Category B parts are used, Mean Time Between Failures (MTBF) numbers in the range of $3.35X10^5$ to $5.48X10^6$ hours were calculated. Using Category C parts reduces the MTBF by a factor of 30.

For the preparation of the FMEA there was insufficient knowledge of specific loads to be controlled by the RPCs to assess the effect of an RPC failure on the electrical system. However, the most critical failure modes were assessed for impact on the desired output condition. Notation was also made of certain failure modes that will result in partial or complete loss of overcurrent protection while the basic switching functions may remain intact.

Table IV provides a summary of the 120 Vdc hybrid RPC designs. It has been estimated that optimization of the Type II design would yield a package volume of 2.24 $in.^3$ and a weight of 3.24 oz. The reason that this volume and weight is not substantially lower than the Type I is due to the capability of the main alloy transistor plus a helper resistor to dissipate heat during current limiting. If this alloy transistor were not available, it would require 10 diffused transistors in parallel to handle the power dissipation. The results would be a size and weight for the Type I approaching the Type III.

SUMMARY OF RESULTS

The program described in this paper has demonstrated technology readiness for 120 Vdc RPCs with current ratings of 5 and 30 amperes. Not only have the electrical designs been demonstrated, but also packaged, hybrid RPCs with good thermal and mechanical designs have been defined. These hybrid RPCs are nearly ready for system evaluations.

The RPCs have been shown to be compatible with essentially any source type - batteries, fuel cells, generators, and solar arrays. They are also compatible with all typical load types, such as; resistive, capacitive, inductive, motors and incandescent lamps. These RPCs have potential application in spacecraft and aircraft electrical systems, in transportation systems, industrial applications and in hazardous areas with volatile gases present.

The many unique features of the solid state RPCs described in this paper lead to immediate power distribution system benefits, namely: lighter weight, reduced size, increased reliability, versatility, and better compatibility of the circuit protection and control devices with source, loads and computer control. The usual drawbacks, high power loss and cost, of solid state RPCs have been minimized with highly efficient and potentially low cost hybrid designs. Since the RPCs would handle several functions, permit shorter bus runs with smaller wires, contribute to longer system life, one would anticipate substantially lower overall system costs when compared to conventional electrical systems even though the RPC itself is yet relatively high in per unit cost.

One final result to be noted is the capability of the Darlington power switch design to be applied to higher voltage systems. The RPC drive and control circuit is readily adaptable in principle to any dc voltage level. The upper voltage limitation on the RPC design is related to the capability and availability of suitable high voltage, power transistors.

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TABLE I. - DESIGN GUIDELINES FOR 120 VDC REMOTE POWER CONTROLLERS

Characteristic	Requirement	Advantage to system
"Contactless" switching with positive control	Solid state/transistor	Reliability, long life, fast response, low EMI, and transient voltages
Darlington switch	Eliminate transformer-oscillator; simplify power circuit	Fewer parts, lower costs, weight, EMI, higher partial load efficiency, wider operating voltage range
Current limiting	3X for 0.1 second plus I^2T limit (see fig. 2)	Reduce wire size, lower EMI, handle loads with high inrush currents
Non-current limiting	5X instant trip plus I^2T limit (see figs. 3 and 4)	Simpler, less costly, compatible with many load types
Controlled rate turn-on and turn-off, dI/dt limiting	Rate of rise less than 0.35 A/μsec (2.5 V/μsec) with no inductors	Reduce transient voltage and EMI generation. less weight and volume, adaptable to hybrid circuits
Trip response	Fast, accurate, and repeatable over temperature extremes	Smaller wire size, smaller power sources, improved power quality
Low level remote control/status;	15 or 28 Vdc control, current sinking status, dielectric isolation up to 1000 Vac from bus power	Shorter power bus runs, compatible with computer control, excellent transient voltage isolation
Series/parallel operation	Coordination of trip characteristics	System compatibility, controlled startup and load shedding

TABLE II. - PERFORMANCE SUMMARY OF THE 120 VDC REMOTE POWER CONTROLLERS

	A. Original design, transformer-oscillator drive			B. Simplified design, Darlington drive			
Item	Type 1	Type II	Type III	Type I	Type II	Type III	Units
Current rating	5.0	5.0	30.0	5.0	5.0	30.0	Amperes
Voltage rating	120.0	120.0	120.0	120.0	120.0	120.0	Volts dc
Operating voltage range	80 to 132	80 to 132	80 to 132	25 to 132	25 to 132	25 to 132	Volts dc
Turn-on voltage	7.5	7.5	7.6	13.5	13.9	13.4	Volts dc
Turn-off voltage	7.4	7.4	7.5	12.6	12.0	12.2	Volts dc
Turn-on time	105	120	150	700	900	1400	Microseconds
Rise time	85	35	145	50	50	90	Microseconds
Turn-off time	80	270	112	1450	660	2000	Microseconds
Fall time	65	35	50	600	260	900	Microseconds
Voltage drop at rated load	0.39	0.50	0.72	1.15	1.16	1.3	Volts dc
Power dissipation at rated load	8.62	6.63	36.5	7.83	6.84	41.8	Watts
Efficiency at rated load	98.55	98.85	98.96	98.7	98.7	98.8	Percent
Current limit level	15.0	N.A.	N.A.	14.5@120 Vdc	N.A.	N.A.	Amperes
Current limit ripple	0	N.A.	N.A.	0	N.A.	N.A.	Amperes
Incandescent lamp start capability	775	275	635	700	300	———	Watts
Fault response time	1.0	3.0	5.0	3	3	5.0	Microseconds
Peak fault current	18.0	68	140	53	60	111	Amperes, peak
Number of electrical components	138	117	120	81	78	86(96)	Parts
Cost of electrical components, based on 1974-100 piece quantities	225	103	119	79	57	75(108)	$

TABLE III. - PERFORMANCE COMPARISON OF ANALOG AND DIGITAL CONTROL/STATUS

CONFIGURATIONS FOR RPC's

Item	Analog system	Digital system
1. Control supply	Constant current	Constant voltage
2. Status indication	Switched resistance at RPM gives different voltage levels when driven by constant current source	Logical "1" or "0" output from RPC
3. Number of wires	2, control and return	min. 3; control, status and common
4. Number of discernable states	Limited only by noise margin and accuracy of analog conversions	2^n, where n is the number of status wires
5. Noise margin	Inversely proportional to number of discernable states	Independent of number of discernable states
6. Status sampling multiplexer (at I/O unit)	Requires relatively slow analog to digital converger plus analog [illegible]	All digital

TABLE IV. - SUMMARY - 120 VDC HYBRID RPC DESIGNS

	Type I	Type II	Type III
Current rating	5 amp	5 amp	30 amp
Current limiting	15 amp	No	No
Basic hybrid package dimensions	1.73 x 1.85 x 0.80 in. high	2.24 x 2.79 x 0.76 in. high	2.24 x 2.79 x 0.76 in. high
Overall package dimensions	2.71 x 1.85 x 1.27 in. high	3.26 x 2.79 x 1.23 in. high	3.26 x 3.26 x 1.23 in. high
Package volume	2.56 $in.^3$	4.75 $in.^3$ (2.24 $in.^3$)	4.75 $in.^3$
Weight	3.50 oz	6.61 oz (3.24 oz)	7.15 oz

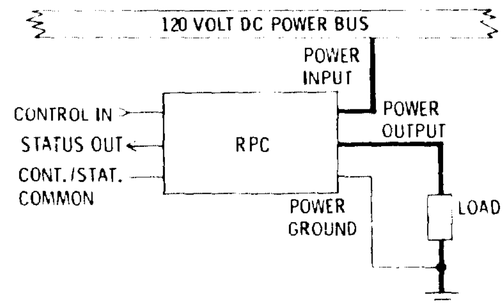

Figure 1. - Typical RPC application. Dielectric isolation up to 1000 volt ac is provided between the low power controls and the high power side of the RPC.

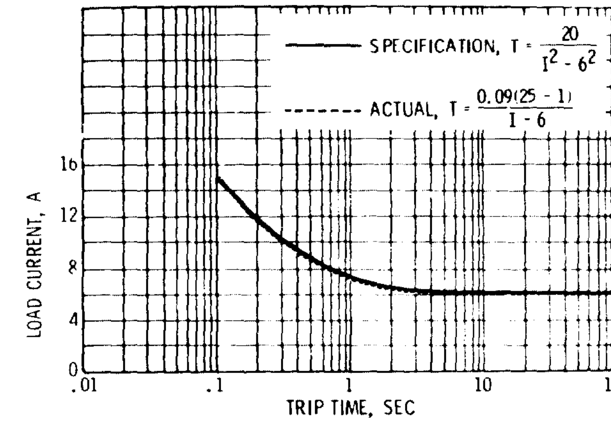

Figure 2. - The inverse trip time relationship for the Type I, 5 ampere RPC stops at 15 amperes because the RPC limits the maximum load current to three times rated current.

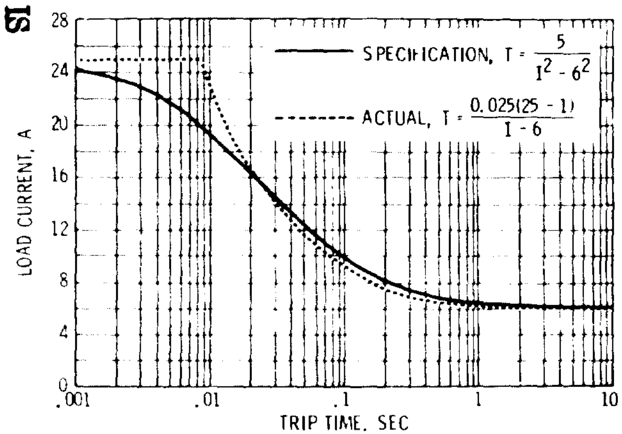

Figure 3. - The inverse trip time curve for the Type II, 5 ampere RPC allows the "instant trip" for overload currents above 25 amperes.

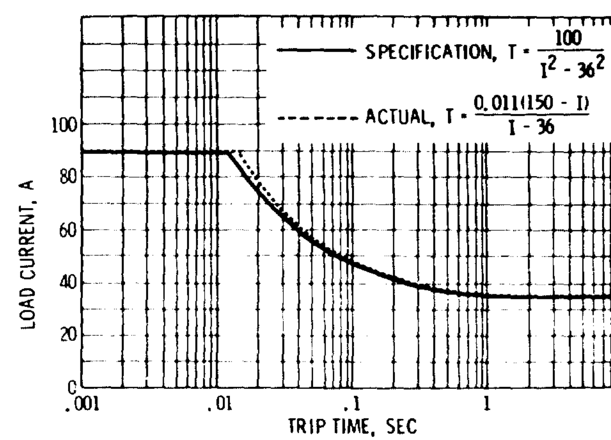

Figure 4. - The inverse trip time curve for the Type III, 30 ampere RPC has an "instant trip" level of 90 amperes.

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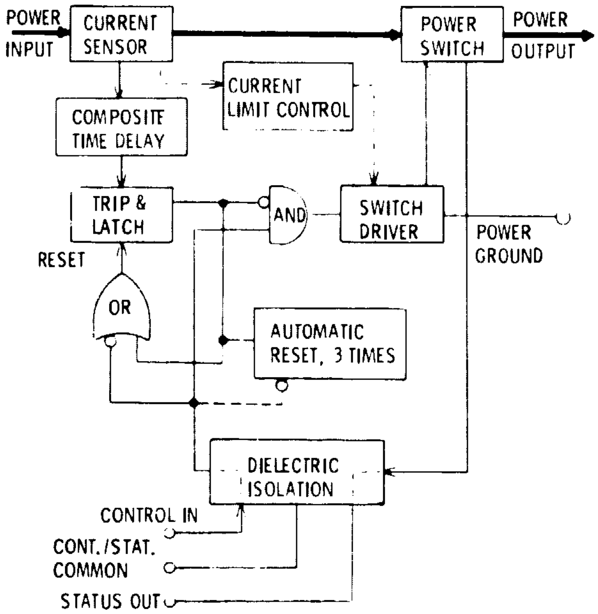

Figure 5. - Each basic function within the RPC is shown by the block diagram. The load is energized and de-energized through the low power control signal input.

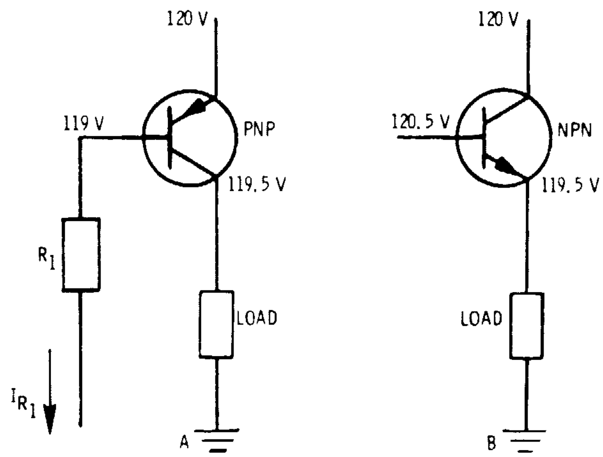

Figure 6. - Of the two basic approaches the PNP offers a low saturation voltage with a simple resistor driver (R_1), however, it is inefficient. The NPN, on the other hand, requires that its base be biased above the 120 volt bus for saturation and, therefore, needs a complex driver circuit.

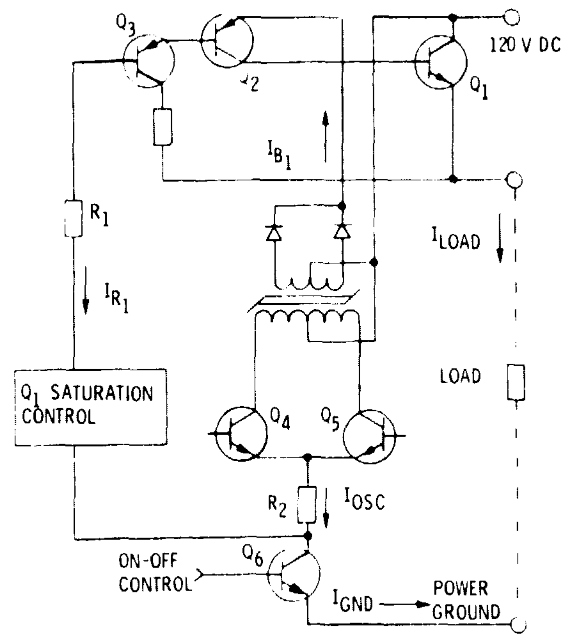

Figure 7. - In the selected power switch the saturation level of Q_1 is controlled by current I_{R_1}. Thus, current limit control is not through the efficiency boosting oscillator and is, therefore, quite fast.

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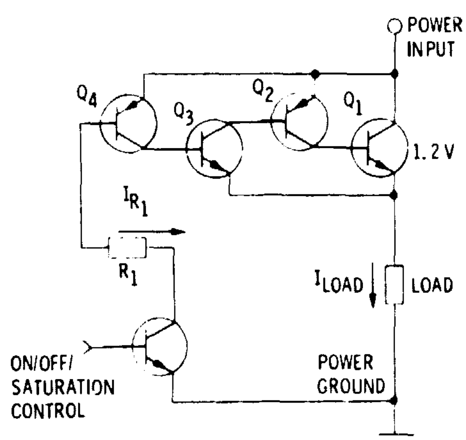

Figure 8. - For the second generation simplified power switch design the saturation level of Q_1 is controlled by current I_{R_1}; the full load saturation voltage is 1.2 volts giving a maximum efficiency of 99 percent for a 120 volt dc system excluding I_{R_1}, which is very small.

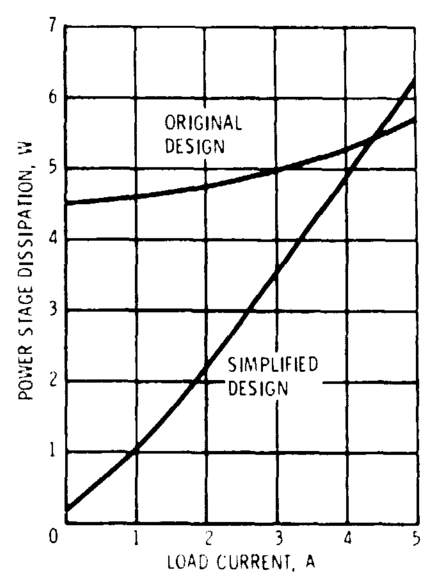

Figure 9. - Partial load dissipation comparison of the original Type I design and the simplified Type I design.

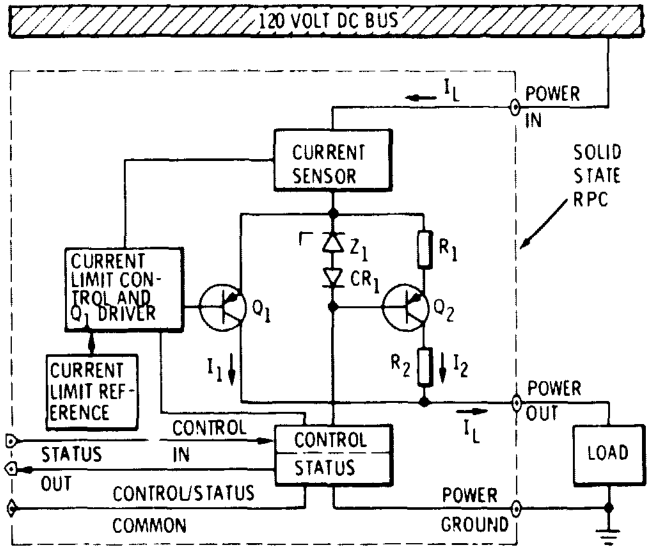

Figure 10. - Safe Operating Area (SOA) booster circuit in a basic RPC switch application. Transistor Q_2 and resistors R_1 and R_2 assist the main transistor Q_1 during current limiting.

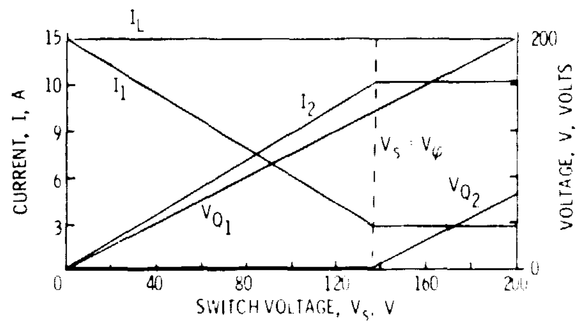

Figure 11. - Performance curves for the SOA booster circuit of figure 10. V_φ is a design parameter.

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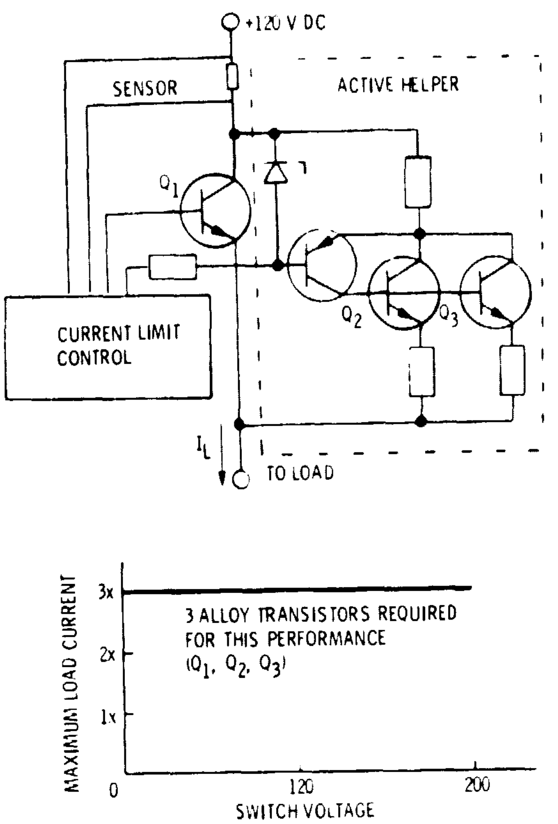

Figure 12(A). - Original Type I RPC power stage concept.

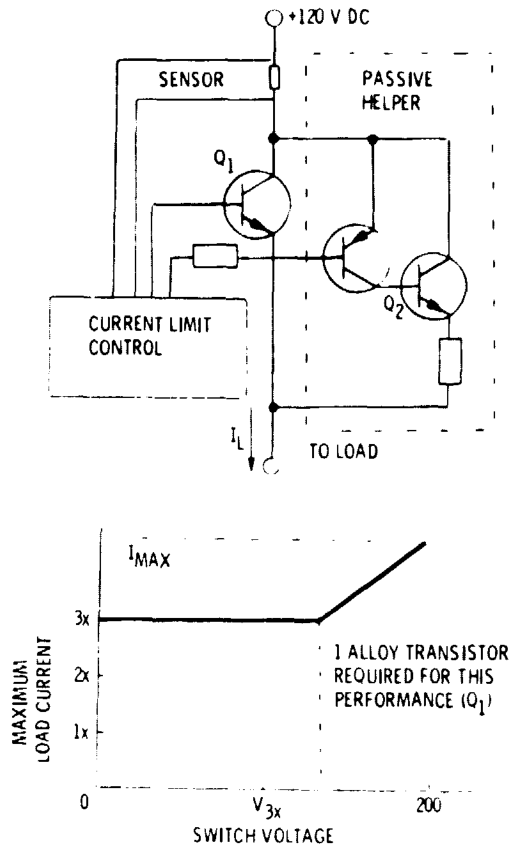

Figure 12(B). - Simplified Type I RPC power stage concept. The simplified current limiting helper is considerably lower cost and offers adequate performance.

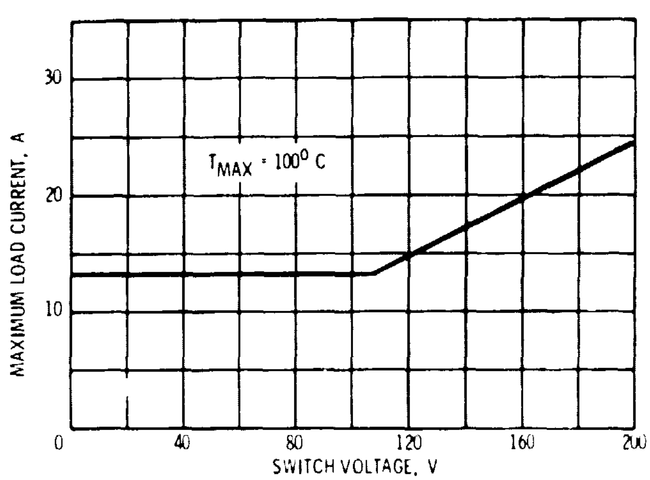

Figure 13. - Final selected current limiting characteristic for the simplified Type I RPC. The maximum current exceeds the desired level only for bus voltage transients above nominal. Hence, maximum current is limited to 15 amperes for normal bus voltage levels.

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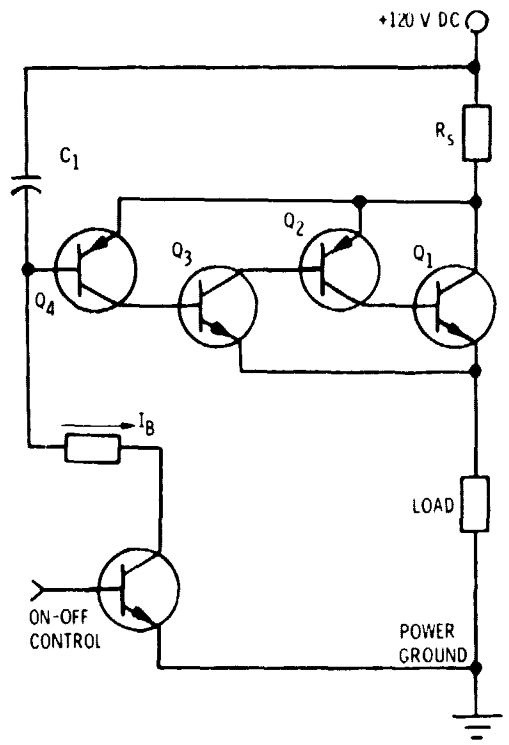

Figure 14. - Power stage concept for the non-current limiting simplified Type II RPC. Similar to the original design, the overcurrent peak for applied faults is limited by R_s and C_1.

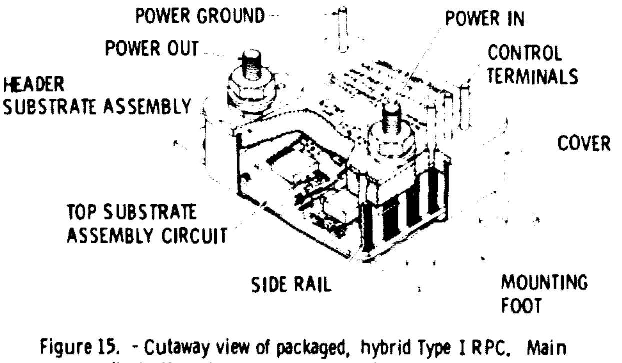

Figure 15. - Cutaway view of packaged, hybrid Type I RPC. Main power dissipating elements are mounted on the underside of the beryllia header substrate. Dimensions are given in Table IV.